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# AN EXPERIMENTAL INVESTIGATION INTO THE ACTION OF DIFFERENTIAL PRESSURE ON CERTAIN MINERALS AND ROCKS, EMPLOYING THE PROCESS SUGGESTED BY PROFESSOR KICK

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SUMMARY

## INTRODUCTION

In a paper which appeared some years ago the results of an experimental investigation into the flow of marble were presented.[1] As this line of investigation seemed to be one which promised to yield additional results of interest if further developed, a grant was made to the present writer by the Carnegie Institution of Washington for the continuance of this work. A more complete equipment for

[1] F. D. Adams and J. T. Nicolson, "An Experimental Investigation into the Flow of Marble," *Phil. Trans. Royal Soc. of London* (1901), Ser. A, CXCV, 363–401.

experimental study was thus secured, the phenomenon of the flow of marble was further studied, and the investigation was extended to other rocks and to various rock-making minerals.

In the present paper it is proposed to describe briefly the results obtained in a single line of the investigation—that in which a method suggested many years ago by Professor Kick was followed. This method, however, while giving certain interesting results, especially with the softer and more plastic rocks, has proved to be less suitable for the development of high differential pressure and for otherwise reproducing the conditions which obtain in the deeper parts of the earth's crust, than the method suggested by the present writer and employed in the research into the flow of marble to which reference has been made. A brief statement of the results obtained by the latter method will appear elsewhere shortly,[1] while the full and detailed results of the whole investigation will eventually be issued by the Carnegie Institution of Washington in a special publication.

In carrying out experiments on the action of differential pressure with a view to reproducing more or less accurately the conditions of pressure which obtain in the deeper parts of the earth's crust, where flow is developed, it is manifestly quite useless to attempt to reproduce these conditions by simply submitting the materials to be investigated to compression in a testing machine, as is done in testing the strength of building stones. Differential pressure is certainly developed in such cases, but it consists merely of the ordinary atmospheric pressure on the sides of the test-piece while the enormously greater pressure exerted by the testing machine acts in the vertical direction. It is necessary to increase the lateral pressure and make it in some degree at least approach the measure of that exerted in a vertical direction if the pressure conditions of the zone of flow in the earth's crust are to be reproduced.

## DESCRIPTION OF KICK'S METHOD

To secure this lateral pressure experimentally Kick[2] devised his method. This consists in making a box of some strong and at the same time ductile metal, such as copper, placing in it a specimen of

[1] See *Amer. Jour. Sci.* (June, 1910), and following numbers.

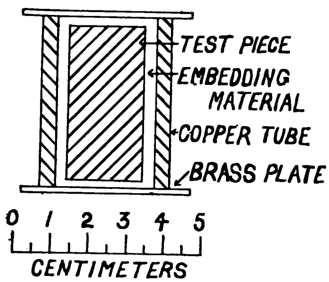
[2] "Die Principien der mechanischen Technologie und die Festigkeitslehre," *Zeit. des Ver. Deut. Ingen.* (1892), XXXVI, 919.

the material to be experimented upon, and then filling the space between the two with some embedding material which may be poured in as a liquid but which on cooling will solidify into a mass which is susceptible of deformation under pressure and which can, at the conclusion of the experiment, be removed by heat or in solution. The whole is then submitted to the action of a powerful press and squeezed down. The resistance to deformation offered by the copper as well as by the embedding material itself is transmitted through the embedding material to the specimen, which thus receives a very considerable amount of lateral support, or is submitted to a very considerable amount of lateral pressure as the deformation proceeds. After the completion of the experiment the embedding material is removed and the specimen recovered and examined. This method is easily followed, experiments can be made quickly, and but little mechanical skill is needed in preparing the materials for the purposes of the experiment. It can, however, be used only in experiments carried out at ordinary temperatures, and it is impossible in using it to determine accurately the pressure to which the specimen is being subjected, for the pressure is divided between the box, the embedding material, and the specimen itself. Furthermore, the pressures which are obtained by this means are not so great as it is desirable to employ in some cases. Kick, however, succeeded in this way in developing permanent deformation in rock salt, talc, gypsum, fluorspar, and marble. Two papers by Rinne,[1] which have appeared more recently and while the present investigation was being carried out, also present an account of certain experiments in which Kick's method was employed and in which rock salt, sylvine, and marble were deformed.

In the present investigation stout copper pipe was used, the standard size known as "one-inch iron-pipe size" being usually employed. This has an internal diameter of 1.063 inches and is made of material having a thickness of 1.125 inches. From this lengths were cut off to suit the specimen to be examined. The piece of tube, having smoothly finished ends, was placed in an upright position on a glass

[1] "Beitrag zur Kenntniss der Umformung von Kalkspathkrystallen und von Marmor unter allseitigem Druck," *Neues Jahrb. für Min.*, etc. (1903), I, 3, s. 160; "Plastische Umformung von Steinsalz und Sylvin unter allseitigem Druck," *ibid.* (1904), I, 3, s. 115.

plate and a portion of the embedding material (molten alum or whatever other material might be selected) was poured into the tube. The portion of the liquid which came in contact with the glass solidified almost immediately, forming a cake at the bottom, and the specimen to be compressed was then inserted into the still unsolidified upper portion of the liquid, in such a position that it would be compressed in the desired direction, and the rest of the embedding material was then poured in quickly so that it would mingle with that already contained in the tube before this had completely solidified. When quite cold and solid, this upper portion, often more or less porous on account of the air bubbles which it contains, was pared away with a knife or filed away by means of a large, coarse, flat file, till the surface was level with the end of the tube. A few smart taps then removed the glass plate from the bottom of the tube thus filled, leaving a flat and polished surface.




When putting it in the press, it has been found best to place over each end of the tube a piece of stout brass plate. Upon the application of pressure the copper tube is first pressed into this plate at either end and a very firm and solid joint is made, the tube becoming converted into a box, from which nothing can possibly escape unless the tube itself is ruptured. The copper tube with its contents ready to be squeezed down in the press is shown in the accompanying figure. In some cases larger and heavier copper tubes of various sizes were employed.

Four different embedding materials were used in these experiments, namely, alum, sulphur, fusible metal, and paraffine wax. All these can be rendered fluid at comparatively low temperatures. Kick employed the two materials first mentioned and he also in some cases used shellac and in others stearine. Each of these substances has certain advantages. On the whole, alum and paraffine wax have been found to be the most suitable and in the present series of experiments have been used in the majority of cases.

Alum, if employed, can readily be removed at the conclusion of the experiment by placing the deformed tube in hot water on a water bath for a short time. But it has the disadvantage when used as an embedding material for limestones, that, whether in a state of fusion or solution, it attacks carbonate of lime to a noticeable extent. On soaking out the contents of the tube with warm water at the conclusion of the experiment, however, a very distinct effervescence always ensues and this is especially marked if the marble has been rendered at all pulverulent. The amount of calcite which is thus dissolved is not, however, great but it is quite sufficient to etch the surface and destroy the polish of the marble or the transparency of the calcite crystal employed in the experiment. In the case of all the more resistant minerals and rocks, this objection of course does not exist.

When sulphur, fusible metal, or paraffine wax is used, these are removed at the close of the experiment by simply heating the tube in a deep porcelain dish, over which a second smaller one is inverted on a sand bath or a water bath as the case may be.

In order to get some clear idea of the resistance to deformation offered by these several embedding materials under the experimental conditions, a series of experiments was carried out on the deformation of copper tubes or collars of the size usually employed, some of which were left empty while others were filled respectively with the several embedding materials referred to above.

The following table shows the results obtained in tabular form. The values are given in pounds and each represents the mean of two closely concurrent experiments.

| | Maximum Load Sustained | Excess of Resistance Due to Contents of Tube |
|---|---|---|
| Empty copper tube................ | 23,250 | ...... |
| Copper tube filled with paraffine wax | 23,800 | 550 |
| Copper tube filled with fusible metal | 29,925 | 6,675 |
| Copper tube filled with sulphur..... | 31,500 | 8,250 |
| Copper tube filled with alum....... | 34,450 | 11,200 |

It is seen in the first place that the copper tube when filled with paraffine wax offers but very little more resistance to deformation than does the empty tube. Under the conditions of the experiment

the paraffine wax develops but little internal friction and moves with comparative ease. With the other three materials the case is very different, a marked resistance being offered to deformation. This is greatest in the case of alum and least in the case of fusible metal. Subtracting the load required to deform the tube itself from that required to deform the tube filled with each substance respectively, it is found that the load required to deform the columns of the three materials in question (inclosed in the tubes under the conditions of the experiment) is that given in the last column of the table. These values calculated in pounds per square inch, using the area possessed by a cross-section of the columns of materials before deformation, which does not differ greatly from that possessed by the ends of the deformed masses, are given in the following table, together with the ratio of their respective strength or resistance which they offer to deformation, reduced to its simplest terms.

| | Lbs. per Square Inch | Ratio of Strength |
|---|---|---|
| Paraffine wax | 620.7 | 1. |
| Fusible metal | 7533.9 | 12.13 |
| Sulphur | 9311.5 | 15.00 |
| Alum | 12641.1 | 20.36 |

In the case of a tube filled with paraffine wax, whenever the smallest fissure develops in the copper tube the inclosed paraffine passes out in the form of a thin, narrow ribbon and continues to issue as a long, graceful, curling band until the pressure is removed. When rupture takes place in a tube filled with alum the contents of the tube are not forced out until the crack has opened considerably, when the alum commences to fall out in a pulverulent condition. In the case of the fusible metal, on the other hand, the rupture of the inclosing tube does not lead to a discharge of the contents through the crack, but the copper tube peels off and the inclosed metal flattens down into a cake having a smooth, rounded surface. A striking fact noted in the case of tubes filled with sulphur is the continued sound of cracking which issues from the sulphur during deformation, a sound which resembles that produced when glass or any other brittle body is similarly compressed. At the conclusion of the experiment, however,

if the copper tube be sawn open the sulphur within is found to be to all appearances as hard and solid as any mass of sulphur could be, although in the mass, here and there, little surfaces can be detected which have a slight shimmer and which are evidently planes of slipping. The cohesion of the mineral along them, however, is to all appearances as great as elsewhere in the mass.

In connection with Kick's process there is one point of some importance to which attention does not seem to have been paid by those who have employed the process. This is the question as to whether, in carrying out the experiment, as the deformation of the cylinder goes forward, the pressure exerted on the specimen is conveyed to it entirely through the embedding material, or whether, in the latter stage of the compression, the specimen is actually nipped between the top and bottom of the tube or box which incloses it, that is to say, between the plates of the press, and is pressed upon directly by these without the intervention of any of the embedding material, or of a mere film which remains and which on account of its thinness exerts no influence.

Any experiment may be arranged so as to have the pressure exerted in either of the above ways, but no distinction seems to have been made between the two cases by former workers. As a matter of fact, however, very different results are obtained as one or other method of experimentation is adopted. If the specimen submitted to pressure continues throughout the experiment to lie entirely surrounded by the embedding material and is not pressed upon by the plates forming the ends of the tube, the value of the differential pressure to which it is subjected depends on the "stiffness" or viscosity of the embedding material, that is to say, on its internal friction. In the present state of our knowledge of the mathematics of plastic flow, it is impossible to calculate accurately the stresses set up in the inclosed specimen; although if movement is taking place in the embedding material the stresses are differential. When, however, the substance experimented upon offers great resistance to deformation, as for instance glass or porcelain, the differential stresses set up in any of the embedding materials hitherto employed are not, under the conditions of experimentation adopted, sufficiently powerful to bring about a deformation of the material. The alum, or whatever

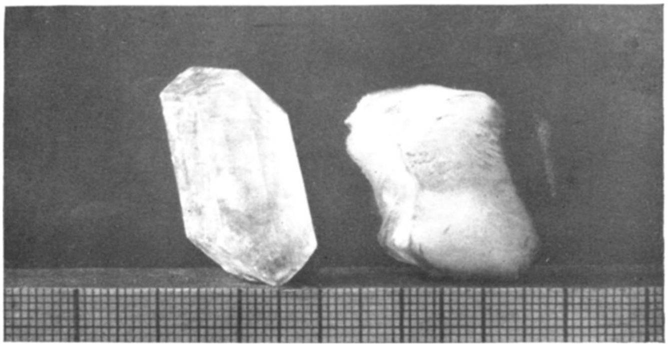
embedding material may be employed, flows around the specimen without producing any effect upon it. If an embedding material could be secured which under compression developed additional "stiffness," the required deformation of the substance might be secured, as when steel is used to inclose the specimen.

When, however, the length of the tube is so arranged that, after bulging has gone forward to a certain extent and the specimen inclosed in it has been submitted to the conditions above described, a point is reached when the top and bottom of the tube, backed by the press plates of the machine, come in contact with the specimen and commence to squeeze it between them, and a much more powerful vertical pressure is brought to bear upon the specimen. Under this, deformation is often produced in a specimen which cannot be obtained by the movements of the embedding material. It may happen, of course, that the vertical pressure thus exerted is relatively too great and the specimen breaks. This pressure, however, may be adjusted so as to yield excellent results.

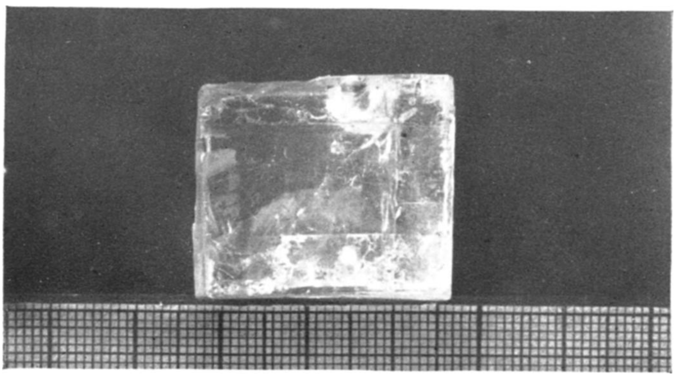
It seems clear that, under the experimental conditions which obtain in Kick's method, it is impossible to arrive at more than a general approximation in endeavoring to estimate the pressure to which the specimen is submitted. The pressure exerted by the machine is divided between the copper tube, the embedding material, and the specimen itself, and the resistance offered by each of these changes continually as the deformation proceeds. It is thus impossible properly to apportion the vertical pressure borne by each of the three elements, and when an attempt is made to go one step farther and estimate the lateral pressure exerted on the specimen by the material which incloses it, many additional and at present insuperable difficulties are encountered.

## DEFORMATION OF CERTAIN MINERALS

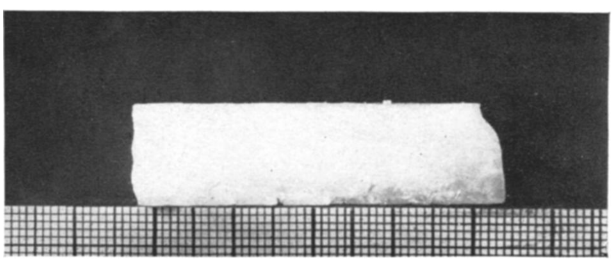
As preliminary to the study of the deformation of rocks, a series of experiments was made on the deformation of rock-making minerals under differential pressure. A number of minerals possessing a progressively greater hardness were selected, with the view to obtaining a series of results, beginning with minerals which are known to be readily susceptible of plastic deformation and passing to others



(*a*) Selenite crystal before and after compression



(*b*) Rock salt crystal before compression



(*c*) Same crystal as in (*b*)—after compression

whose capabilities in this direction are as yet unknown and then to still harder minerals which are considered to be perfectly brittle, so far as this property is known to be possessed by any body in perfection. The mineral species chosen were for the most part those constituting Mohs's Scale of Hardness, although certain others were also included in the list. The series was as follows:

| Name of Mineral | Hardness Mohs's Scale | Name of Mineral | Hardness Mohs's Scale |
|---|---|---|---|
| Selenite | 2 | Limonite | 5–6 |
| Rock salt | 2.5 | Orthoclase | 6 |
| Iceland spar | 3 | Magnetite | 5.5–6.5 |
| Fluorite | 4 | Pyrite | 6–6.5 |
| Apatite | 5 | Quartz | 7 |
| Diopside | 5.5 | Garnet | 6.5–7.5 |

The same body would undoubtedly give different values for plasticity if tested in different ways, just as the same body gives different values for the breaking point, according to whether the latter is measured by bending, tension, or impact.

Speaking generally, however, under ordinary conditions of temperature, hardness is a function of plasticity and minerals become less plastic as they become harder.

*Selenite.*—A clear transparent crystal from Ellsworth, Ohio, was selected. It was perfect in form, being bounded by the prismatic faces in combination with the clinopinacoids and clinodomes. The crystal measured 1.246 inches (31.6 mm.) in the direction of the vertical axis, and 0.618 inch (15.68 mm.) in the direction of the ortho-diagonal axis. This was placed in a copper tube 1.75 inches (44.45 mm.) high and otherwise of the standard size commonly employed in these experiments, namely, having an internal diameter of 1.062 ($1\frac{1}{16}$ inches, or 26.98 mm.), the walls of the tube being 0.125 ($\frac{1}{8}$ inch or 3.175 mm.) thick.

The crystal was placed in the tube on end, as shown in Plate I, Fig. *a*, so that it rested on the lower solid angle, the line of the intersection of the clinodomes being inclined at a considerable angle to the plane of the end of the inclosing tube. Paraffine wax was used as an embedding material, since alum, sulphur, or fusible metal melts at temperatures above that at which selenite loses its water. The paraffine wax, melting at a temperature below that of boiling water,

was poured around the selenite crystals until the tube was filled, the usual precautions already referred to being observed, and a brass plate was placed on either end, when it was inserted in the press and served as a top and bottom to the tube. The pressure being gradually raised, a large ring-shaped bulge gradually developed near one end of the copper tube, and eventually the metal began to tear open at one point on this bulge. The pressure was then taken off, the tube removed from the press, the paraffine melted away, and the selenite crystal obtained. The crystal was found to have undergone a very marked deformation.

In order to obtain further deformation, the crystal was then placed in the same position in another tube, having the same diameter as that formerly employed but only 1.5 inches (38.1 mm.) high, and this, after the residual space had been filled with paraffine, was compressed in the same manner as before. In this shorter tube a further deformation of the selenite was secured. The maximum load employed was 24,000 pounds (10,872 kilos), and the total time during which deformation was actually going forward was 70 minutes. The selenite crystal, after removal from the tube, is shown in Fig. *a*, Plate I, there being placed beside it another crystal of the size and shape which it originally possessed. It will be seen that the acute solid angles of the monoclinic prism have been turned back by movement along a plane coinciding approximately in direction with an orthodome, while both ends have also been bulged out laterally and the whole crystal has also been slightly curved. There are no traces of fracture, tearing, or cleavage, but the surface of the crystal—more especially in those parts which are most deformed—is minutely wrinkled. The extremities of the crystal, where the deformation is most intense, have for the most part lost their transparency and are now translucent.

In the case of selenite, therefore, deformation under differential pressure can be produced readily and at comparatively low pressures. It is certain that in the case of the selenite crystal in question, a much greater deformation might have been secured by placing the crystal in successively shorter and wider copper tubes as each showed signs of rupture, and thus flattening it out by stages.

*Rock salt.*—A large cleavage cube of clear transparent rock salt

was taken. This measured 1.378 inches $\times$ 1.18 inches $\times$ 1.38 to 1.389 inches (35 mm. $\times$ 30.05 mm. $\times$ 35.05 to 35.3 mm.). It was inclosed in paraffine wax in a copper tube in the usual way. This was squeezed down until it showed signs of rupture when the salt crystal, now considerably flattened, was removed and placed in paraffine in another shorter but wider tube, which was in its turn squeezed down until rupture threatened, when the crystal was removed to a third and still wider piece of copper tube, in which the deformation was completed, the maximum load employed being 157,000 pounds.

The salt when removed was found to have the form of a continuous flat cake, nearly square in section. It now measured 0.56 inch (14.2 mm.) in thickness and was 2.215 inches to 2.25 inches (53.97 mm. to 57.15 mm.) by 2 inches to 2.125 inches (50.8 to 53.975 mm.) in diameter. Photographs of the crystal as it appeared before and after deformation are shown in Plate I, Figs. *b* and *c*. Although a solid mass, quite firm and hard, it had developed a series of fissures extending from both the lower and upper surfaces into the mass, these being wedge shaped in form and following the direction of the faces of the cube, i.e., running parallel to the longer sides of the flattened crystal. These fissures did not pass completely through the crystal from top to bottom, but often penetrated into it deeply. Neither were they continuous from side to side, but were interrupted and crossed each other at right angles. They were not seen on the narrow edges of the mass.

The deformed crystal of salt was brightly translucent but not actually transparent, and the sides of the flattened crystal were in several places beautifully curved. The remarkable plasticity of the salt not only is shown by the manner in which the crystal was flattened out, but is seen in a striking way where the cube, having been carried against the sharp incurving edge of the spreading end of the tube in one place, took an impression of the latter in the form of a deep, sharp-angled, and smooth-faced groove crossing the corner of the salt cube, the impression being as sharp as if it had been taken in wax.

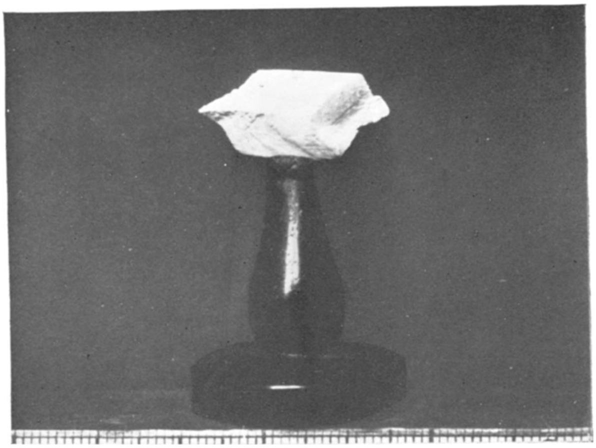
In the present case it was found inadvisable to carry the deformation of the salt any farther, since the little fissures mentioned above having once formed, the downward pressure forced the paraffine into them, and thus tended to divide up the salt crystal by a series of

paraffine wedges driven into it. Even in this case, the crystal would develop a filigree pattern; but if the conditions of the experiment be slightly altered so as to prevent the formation of the wedges of paraffine, it is believed that a salt crystal, on account of its great plasticity, might be flattened out to almost any required extent and might be molded into any desired form.

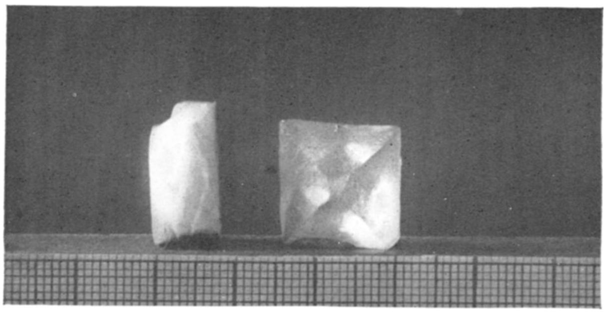
*Iceland spar.*—Since in considering the deformation of marble the effect of differential pressure on the constituent calcite grains is described, it is unnecessary here to repeat these descriptions. It may, however, be of interest to refer to a single experiment on the deformation of a large cleavage fragment of Iceland spar.

In this a cleavage rhombohedron of Iceland spar, measuring 0.73 inch (18.54 mm.) between the acute angles of the rhombohedron, was embedded in alum in a copper tube of the usual type, having a height of 1.25 inches (31.75 mm.), and a wall thickness of 0.125 inch (3.175 mm.), the tube being closed by a thick plate of cast iron placed against one end and a plate of machinery steel placed against the other, the rhombohedron being so set that its acute edges would come against the metal plates at either end as the deformation progressed. The tube was then squeezed down to a height of 0.473 inch (12.01 mm.), under a load of 83,000 pounds. On dissolving away the alum it was found that the calcite rhombohedron had been pressed into the metal plates at either end, leaving a faint but clearly perceptible impression on the machinery steel at one end and a somewhat more distinct one in the cast iron at the other. Neither of these, however, was so distinct as those produced by the fluorite (see below). The edges of the calcite which produced the indentations remained quite sharp and showed no granulation, but the crystal under the pressure has been converted into a perfect twin crystal, the plane of twinning being at right angles to the direction of maximum pressure (see Plate II, Fig. *a*).

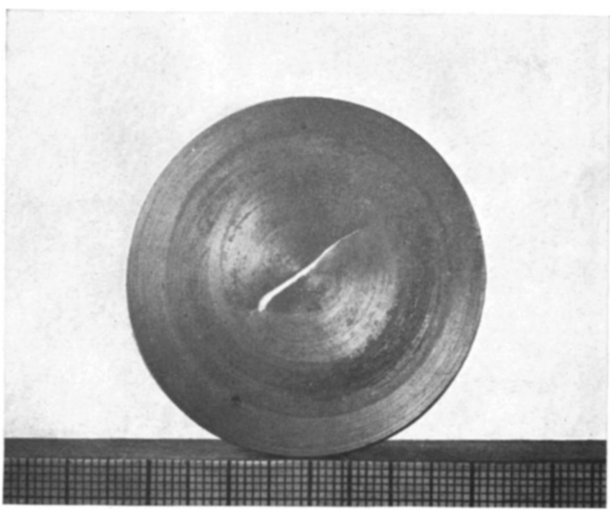
*Fluorite.*—Passing to the next higher member of Mohs's Scale of Hardness, the action of differential pressure on fluorite was investigated. Five experiments were made with this mineral. For the first, a group of twinned fluorite crystals, green in color and consisting of three interpenetrating cubes from Weardale, Durham (England), was selected, the largest of these crystals being 0.82 inch (20.8 mm.)



(*a*) Twin of calcite produced by compression



(*b*) Fluorite crystal before and after compression



(*c*) Nickel steel disk penetrated by the edge of a crystal of fluorite

in diameter. This was placed in a copper tube, 1 inch (25.4 mm.) high and otherwise of the same dimensions as those usually employed, namely 1.0625 inches (26.98 mm.) in internal diameter, and having a wall 0.125 inch (3.175 mm.) thick. Melted alum was used as an embedding material and a brass plate was used to form the top and bottom of the tube. The whole was then placed in the press and squeezed down until the tube was reduced to 0.75 inch (19.05 mm.) in height. When, this, having assumed a symmetrical bulge, commenced to develop minute fissures in its most distended portion, the experiment was brought to a close. The time occupied in the deformation was 50 minutes, the pressure being gradually raised until it reached a load of 42,500 pounds. On dissolving away the alum, the group of fluorite crystals was obtained as a firm coherent mass, but the deformation had been so great that while portions of two cubes could be recognized, the rest of these two cubes and the third cube had been so welded together into a lump that it was impossible to distinguish them or to ascertain which part of the mass they represented. The green color of the original mineral had disappeared except in one or two spots, and its place had been taken by a pale violet tint, and the mineral, which was originally transparent to translucent, had become practically opaque.

A thin section of the deformed mass was then prepared, which, when examined under the microscope, showed that the fluorite was still clear and transparent, except along a few lines which traversed the slide in sinuous curves. Here the mineral presented a turbid appearance. The three individuals composing the mass were seen to be traversed by their respective cleavage lines, evidently developed in grinding the section, which made it possible to determine their boundaries in a general way. Each cleavage line was seen to follow a straight course, until it approached the turbid lines above mentioned, when it bent with a sharp curve or sudden twist; the crystal along these lines where the movement was greatest being broken into a mass of minute grains, still, however, firmly coherent. When examined between crossed Nicols the fluorite was seen to remain perfectly isotropic, except along the lines of most intense movement and granulation, where it can frequently be seen to be distinctly doubly refracting.

It is thus evident that the mineral fluorite is plastic to a marked degree. It may be bent and twisted without any signs of disruption and it is only along certain lines of very intense movement that the mineral breaking develops a cataclastic structure, just as marble does in places when deformed under low differential pressures. The little broken grains of fluorite thus produced, however, as in the case of the marble, remain firmly coherent, and it is highly probable that, as in the case of marble, if the deformation were carried on under much higher pressures or at a higher temperature, fluorite could be deformed without any fracture or the development of any cataclastic structure whatsoever.

While, however, the plasticity of the mineral is remarkable, its resistance to movement and the force required to bring about its deformation appear to be considerably greater than in the case of calcite, and it was observed that an angle of one of the fluorite crystals which cleared itself from the alum and came into contact with the brass plate at one end of the tube made a distinct triangular depression in it.

Several other experiments with a perfect cleavage octahedron of fluorite from Westmoreland, Cheshire Co., New Hampshire, carried out under identical conditions, resulted in the flattening of the rhombohedron, the movement being of the nature of a plastic flow, except possibly where here and there a few little opaque white lines indicated the development of a minute cataclastic structure. In these experiments also the fluorite showed the same stiffness or resistance to deformation, which was seen not only in the very high pressure required to deform it, but also in the fact that as the copper tube was squeezed down and the alum flowed away from above and below it, leaving the mineral in contact with the brass plates at either end, the octahedral faces of the mineral, where they came upon the brass plate below, sank into it, leaving a well-marked depression, while the two octahedral edges bounding the face in contact with the upper brass plate, which was 0.075 inch (1.9 mm.) thick, cut completely through it, leaving a wide rent, and having passed through this plate, forced their way into a second brass plate behind it.

Another experiment employing much higher pressures was then made by taking an octahedron of fluorite, similar to that employed

in the last experiment, and inclosing it in alum in a piece of thicker copper tube. This tube was 0.75 inch (19.05 mm.) high, and made of metal 0.187 inch (4.65 mm.) thick. The octahedron was set in the alum so that it rested on an edge. For the ends of the tube, instead of brass plates, plates of steel were used. That at the bottom of the tube was made of machine steel one inch (25.4 mm.) thick, and that at the top was a plate of nickel armor steel 0.063 inch (1.6 mm.) thick. The tube was slowly squeezed down to a height of 0.384 inch (9.75 mm.). This occupied 30 minutes, the load finally reaching 112,000 pounds (50,804 kilos). The fluorite octahedron was found to have been squeezed into a nearly square tabular mass (Plate II, Fig. *b*) measuring about three-quarters of an inch across, the movements being of the same nature as those described in the last experiment. Crossing the top and bottom of this mass diagonally were two faint ridges representing a survival of the edges of the octahedron. These by the pressure had been brought into contact with the steel plates at either end of the tube and had actually embedded themselves in the latter, the upper and sharper edge sinking into the nickel steel, leaving a deep, well-marked depression in the steel along its whole length (Plate II, Fig. *c*), and at the same time distinctly bending the plate. The lower edge, which was blunter, left a similar depression in the machine steel below. These edges of the fluorite crystal, although having in this way forced themselves into the steel, showed no signs of breaking or granulation, but were intact. It would without doubt be possible, by changing the conditions of the experiment somewhat, to force a crystal of fluorite completely through a piece of steel armor plate.

As in the other experiments, the color as well as the form of the mineral was found to have been altered by the pressure. Two of the opposite solid angles of the octahedron still retained a green color though much paler than before, but the rest of the flattened crystal, including the edges which had embedded themselves in the steel, that is to say, that portion of the mineral which had been submitted to the most intense pressure, was found to have assumed a distinct violet or purple color.

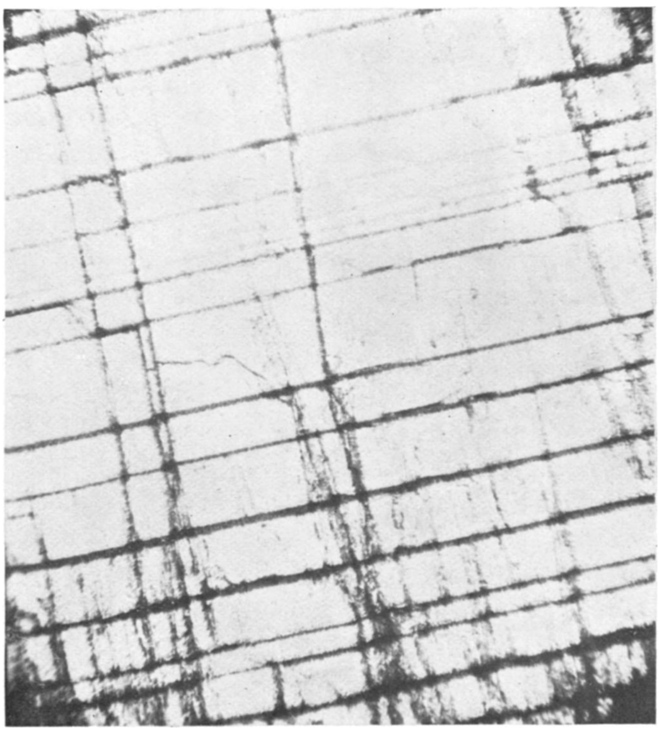
Another experiment, in which paraffine wax was used instead of alum as an embedding material, showed that with this medium a

similar distortion of the fluorite was produced while the green color of the original mineral became much paler. The change in color of the fluorite which, as noted above, was produced in every instance by the pressure is a very curious phenomenon. In three of the experiments the change consisted in the substitution of a much paler tint of green for the deeper green color which the mineral possessed originally. In the other two cases, where the deformation had been if anything more intense, the original green color actually changed to pale purple or violet, a color which is often possessed by the fluorite from Derbyshire and elsewhere. The reason for this change is unknown and will probably remain so until the nature of the fugitive colors displayed by this mineral have been discovered. It was at first thought that the change in question might have been brought about by the heat of the molten alum in which the mineral was embedded and that it might thus have been induced before the pressure had been applied. Crystals of the fluorite from both localities were accordingly taken and embedded in molten alum in the usual way, but it was found on removing the alum by solution that no change in color whatsoever had resulted from this treatment. The change in color therefore must be due solely to the action of pressure.

*Apatite.*—A small crystal of opaque greenish apatite from one of the Canadian localities, probably in Ottawa County, Quebec, measuring a little less than 1.25 inches (31.75 mm.) in height, and about 0.5 inch (12.7 mm.) in diameter, was selected. The crystal showed the usual prismatic and pyramidal faces seen in the specimens from this district, as well as small basal planes. It was placed, resting on one of the pyramidal faces, in a copper tube of the same dimensions as that employed in the last experiment, but 1.25 inches (31.75 mm.) high. The tube was then filled up with molten alum in the usual way and brass plates were placed at either end. The whole was then slowly squeezed down until the tube showed signs of rupture, the time occupied by the deformation being 55 minutes and the maximum load being 43,000 pounds (19,405 kilos).

On dissolving away the alum the apatite crystal was found to have been crushed to a coarse powder at either end. The central part—representing about one-half of the original crystal—however, remained as a solid mass, and showed portions of the six prismatic faces. Crossing

(*a*) Microphotograph of a thin section of a diopside crystal before compression. Between crossed Nicols



(*b*) Microphotograph of same, after compression. Showing the development by the pressure of polysynthetic twin lamellae

this remnant of the crystal approximately parallel to a pyramidal face, and thus in a direction approximately at right angles to the direction of pressure, some half-dozen planes could be seen along which movement of the nature of a minute faulting had taken place. The mineral, however, was firmly coherent where traversed by these planes, indicating that apatite under the experimental conditions, although breaking along certain lines, was firmly welded together again by the pressure and was thus slightly plastic. A further evidence of plasticity is afforded by the fact that one of the prismatic faces shows a slight but distinct bending or curving.

The evidence afforded by the experiment, therefore, shows that while apatite is very much more brittle than the softer minerals of the series, it nevertheless possesses the property of plasticity in a slight degree at least, a conclusion which is confirmed by the occasional discovery of apatite crystals which are distinctly curved or bent in the highly contorted crystalline limestones and associated rocks of Laurentian age in the Ottawa district. That the mineral is, however, but slightly plastic even under the conditions of very great pressure which obtain during the contortion of the limestones above mentioned, is shown by the fact that the curved crystals to which reference has been made are always found to be broken when the bending becomes very pronounced.

*Diopside.*—A number of clear crystals of pale green diopside from De Kalb, New York, were secured, and from these two were selected. These, together with an octahedron of magnetite from Mineville, New York, were embedded in alum, inclosed in a copper tube, and submitted to pressure in the usual manner adopted in Kick's method. The copper tube was 0.877 inch (22.29 mm.) high, but otherwise of the same dimensions as that employed in the case of apatite—the experiment being carried out in the same manner. The diopside crystals were quite transparent and showed both pinacoids, the prisms, two sets of domes, and one set of pyramidal faces. One of these crystals was placed in the tube so as to lie upon its orthopinacoid, the direction of the pressure being consequently at right angles to this face; while the other was placed so that the pressure would be exerted upon it in a direction as nearly as possible at right angles to the base. The pressure was continued until the copper tube commenced to show

signs of rupture, the time occupied by the experiment being about one hour, and the load finally rising to 48,000 pounds (21,773 kilos). On removing the test from the press, it was found that the end of one crystal of pyroxene was protruding slightly from the alum and had sunk into the brass plate, leaving a distinct impression in it; and, on dissolving away the alum, it was found that both pyroxenes displayed a twinning parallel to the base which had been developed in them by the pressure; this being strikingly seen in the case of the crystal which was compressed approximately in a vertical direction. The twinning in the case of this crystal appeared as a series of little parallel lines crossing the lateral faces in the direction of the base, and in appearance resembling closely the basal parting so frequently seen in pyroxenes which occur in the limestones of the Grenville series and other rocks which have been submitted to great compressive stresses.

A section was then cut through this crystal in a vertical direction. Under the microscope, between crossed Nicols, this was found to be so orientated as to intersect the crystal in a direction between the orthopinacoid and a prismatic face. The prismatic cleavages were well seen and a second set of interrupted cleavages crossed these at right angles or nearly so, being parallel to the base. Parallel to these latter was a beautiful series of clear, sharply defined, polysynthetic twin lamellae, which had been developed by the pressure. The section was 14 millimeters wide, and in this width displayed 140 twin lamellae, each of which was wide enough to show clearly its individual character, the series being spaced at nearly equal distances across the crystal. Their appearance under the microscope is shown in Plate III, Fig. *b*, while Plate III, Fig. *a*, shows the apearance of a section of the original pyroxene. Apart from the twin lamellae, the mineral shows a slightly undulating extinction, and the section is crossed in one or two places by narrow lines of granulated material, along which, under the pressure, the mineral has broken with the development of a cataclastic structure. A study of the section shows that probably the twinning was first developed and that the mineral under further pressure broke along certain lines. The partial loss of transparency observed in the deformed crystal is largely due to the development of similar lines of broken material, especially at the

ends of the specimens where this loss of transparency is most pronounced.

It is thus evident that under the differential pressure the diopside crystals became slightly twisted, and then, as the pressure increased, changed their shape somewhat by the development of a series of polysynthetic twin lamellae, finally breaking along certain lines, with the development of cataclastic structure. In a paper published in 1886, Mugge[1] describes some experiments which he carried out on the behavior of diopside under pressure. He inclosed clear and untwinned crystals of this mineral in lead and then squeezed the mass down by means of a powerful screw press. In some cases he found that the mineral was reduced to a powder, and in other cases the crystal survived, but, even after repeated trials, he was unable to induce any twinning in it. In some few cases, in the partially crushed crystals, he found what was apparently a twinning parallel to the base. He states, however, that he could very rarely get a section of the twinned material so thin and with the lamellae so broad that the individual lamellae showed their own optical orientation, their existence being indicated merely by the fact that between crossed Nicols the extinction was never complete. It is possible, however, as above described, by employing Kick's process, to obtain in diopside a perfect twinning, in which clear, well-defined lamellae extend through the whole individual and are identical in character with those seen in the twinned diopsides found in crystalline limestones which have been subjected to orogenic movements.

*Limonite.*—A cube, pseudomorph after pyrite, from a locality in Virginia was selected. It was treated in precisely the same manner and in a tube of the same thickness as in the case of the apatite and diopside. On dissolving away the alum, the cube of limonite was not found to present any distinct evidence of plastic flow. Its lower surface was intact except for the presence of a minute crack. The upper surface was traversed by many minute open fissures which crossed one another, giving rise to a rudely rectangular pattern. Each rectangle formed the base of a wedge of the material which was driven downward, causing the sides of the cube to slant outward.

[1] "Ueber künstliche Zwillingsbildung durch Druck am Antimon, Wismuth und Diopsid," *Neues Jahrbuch für Mineralogie* (1886), I, 183.

It is evident in this case that while there may have been some slight plastic deformation in portions of the cube, the movement has been essentially one which has taken place along planes of fracture.

*Orthoclase.*—The crystals used in this experiment were from Good Springs, Lincoln County, Nevada. They were of simple form and very symmetrical development, being bounded by the clinopinacoids, the basal faces, and the unit prisms.

Three of the crystals were placed together in the same copper tube, one lying on a clinopinacoid, one on a prismatic face, and one on its basal plane. The experiment occupied one hour and forty-five minutes. Alum was used as the embedding material and the maximum load—which was of course that reached at the conclusion of the experiment—was 195,000 pounds (88,455 kilos). As the compression slowly proceeded, faint cracking sounds were frequently heard from the interior of the tube. On removing the brass plate, the outlines of the crystals could be seen in the alum at either end. At one end they were for the most part still covered by a thin film of alum, while at the other end they had been forced into the brass plate, deeply indenting it; while one of the crystals, in which a sharp edge came against the brass plate, had forced its way through this plate, tearing it completely open. These portions of the crystal in contact with the brass plates showed no signs of fracture. On dissolving away the alum, however, all three crystals were found to have been much crushed in places.

The crystal which lay upon the prismatic face still held together but was traversed by several little fissures which had their courses chiefly parallel to the base and to the clinopinacoid, that is, in the direction of the normal cleavage of the mineral. They did not, however, invariably follow these planes, but in some cases ran irregularly across the crystal. The individual which lay upon its clinopinacoid had crumbled to pieces. The largest of these pieces showed little cracks parallel to the base and to the clinopinacoid and others running in the direction of the orthopinacoid. The crystal which rested upon its basal plane was reduced to a mass of little fragments without definite form.

Two thin sections were prepared from the first and second of the crystals respectively, in order to ascertain whether any further evi-

dence as to the character of the movement which had taken place could be obtained by a microscopic study of the crushed mineral. The sections in both cases were cut parallel to the orthopinacoid, while, for purposes of comparison, a third section running in the same direction was prepared from one of the original uncrushed crystals. Under the microscope the crystals which had been subjected to compression were seen to be traversed by a number of minute cracks, and also showed in the much-crushed portions faint strain shadows, when examined between crossed Nicols. It is evident, therefore, that under the conditions of the experiment, the orthoclase, while probably displaying a very slight plastic movement of the nature of twisting, as shown by the slightly uneven extinction produced by the pressure, moves almost entirely by fracture and granulation. This agrees with the deportment of orthoclase as observed in highly deformed rocks in the earth's crust, the mineral in these rocks being usually granulated or recrystallized under conditions of differential pressure.

*Magnetite.*—A perfectly symmetrical octahedron of this species from Mineville, New York, was, as mentioned above, embedded in alum and submitted to pressure, with the diopside crystals whose behavior has already been described. On dissolving the alum, the magnetite was found to have been broken to pieces, the fragments having the form of little plates which had separated from the crystal parallel to the octahedral faces.

*Pyrite.*—The pyrite employed was from the Saratoga Mine, Gilpin County, Colorado. The fragment selected had the form of a half cube, showing the crystal faces, with a surface of fracture on one side. The specimen, with the edge of the cube upward, was embedded in alum in a copper tube with a brass plate at either end. Pressure was then applied, the deformation of the tube occupying 17 minutes, and the maximum load attained being 43,000 pounds (19,404 kilos). No sounds whatever issued from the tube as the deformation went forward. On removing the highly bulged tube from the press, it was found that the edge of the pyrite crystal, referred to above, had passed completely through the brass plate and had cut into the iron head plate of the press, the edge, however, remaining practically intact. On dissolving away the alum, it was found that

the lower portion of the crystal, still embedded in the alum, had been much crushed, the original crystal being now represented by one large fragment and a considerable quantity of fine powder. The pyrite, therefore, was crushed without showing any trace of plastic deformation.

*Quartz.*—A clear transparent individual of rock crystal from Hot Springs, Arkansas, was selected. It was embedded in alum in the usual way in a copper tube. The crystal was placed in a somewhat slanting position in the tube, so that it stood approximately on a pyramidal face. The pressure was raised gradually and the load used was just sufficient to start and maintain a very slow bulging of the tube. The pressure was continued for an hour and twenty minutes, by which time the height of the tube had been reduced to 1.37 inches (34.8 mm.), the maximum load employed being 34,000 pounds (19,404 kilos). Once only during the deformation was a faint cracking sound heard in the tube. On removing the alum, the quartz crystal was found to be still coherent with the exception of a few little fragments which had broken off from one end. The crystal, however, was traversed by a large number of cracks following directions approximately parallel to the rhombohedral faces, many of them not passing completely through the crystal, but running only a certain distance and being intersected by others crossing them. It is known that quartz when heated and suddenly cooled develops a tendency to rhombohedral cleavage; but it is also true that when a rigid or an imperfectly plastic body is submitted to pressure it tends to shear along planes which cross one another at an angle approximating to 90°. Whether in this case a tendency to movement along rhombohedral planes was developed, or whether the movement is one quite independent of crystallographic considerations, is uncertain. There was certainly, however, no indication of plastic flow.

*Garnet.*—The last mineral examined, being also the hardest, was garnet, a perfect rhombic dodecahedron of almandine from Bödo, Norway, being selected. It was embedded in alum in the usual manner, the whole being inclosed in a copper tube. The deformation of the tube occupied 50 minutes and the maximum load required was 175,000 pounds (79,383 kilos). A slight cracking sound was emitted at times as the experiment was going forward. On dissolving the

alum, the greater part of the crystal was found to have been reduced to a fine powder. There were a few larger fragments surviving but these showed no signs of distortion. The fragments when examined between crossed Nicols were found to be perfectly isotropic. The garnet, in fact, had been crushed and displayed no traces of plastic deformation.

## DEFORMATION OF ROCKS

Seeing, as has been shown, Kick's method is not adapted for the development of plastic deformation in materials which are very hard, the rocks selected for examination were chiefly of the softer kinds, marbles, limestones, and dolomites of different varieties. The harder rocks were, however, represented by a typical granite. In these experiments columns of the rock were usually employed. These were 1.575 inches (4 cm.) long and usually 0.787 inch (2 cm.) in diameter, with a smooth and generally a polished surface. The copper tubes employed were somewhat larger than the column so that the alum might completely inclose the latter, and had an internal diameter of 1.06 inches (27 mm.) and a wall thickness of 0.125 inch (3.175 mm.). In some cases, as will be mentioned, cubes, prisms, and spheres of the rock were also deformed.

### A. MARBLE: CARRARA, ITALY

This is the same white statuary marble which was employed in a former investigation and described in a former paper.[1] In the case of the large spheres, however, a somewhat commoner variety from the same locality was employed, since blocks of the statuary marble of requisite size for the preparation of these spheres could not be obtained.

#### I. COLUMNS

Columns of the marble were first used and the effect of various kinds of embedding material was studied.

(a) *Deformation with paraffine as an embedding material.*—The maximum load required for deformation of the tube with its inclosed

[1] F. D. Adams and E. G. Coker, "An Investigation into the Elastic Constants of Rocks, More Especially with Reference to Cubic Compressibility," *Carnegie Institution of Washington, Publication No. 46* (1906), 26.

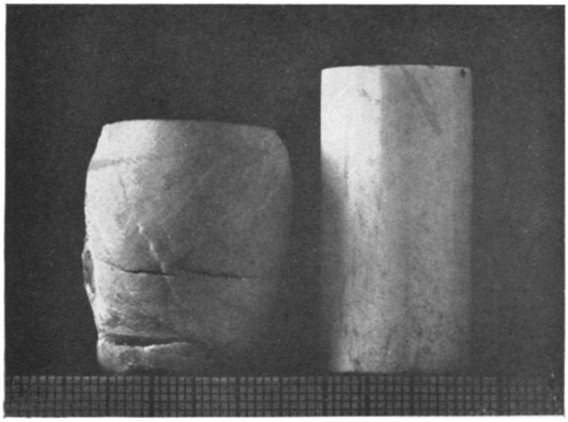
marble and embedding material in these experiments was 30,500 pounds.

The column after deformation, when removed from the paraffine, displays a very characteristic shape, and one which is quite different from that shown by the rock when deformed in alum. The movement set up in the column commences at one end and gradually extends toward the other end of the column, not however as a general rule reaching this before the experiment has to be brought to a close on account of the impending rupture of the copper tube.

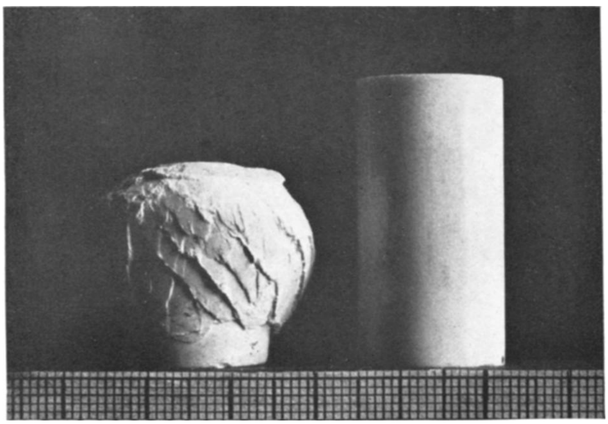
This movement results in the development of a symmetrical enlargement of that part of the column affected, the greatest diameter being a short distance from the end of the column. The deformed portion of the column thus swells out into a more and more pronounced bell-shaped form, which fades away into the unaffected portion of the column, which latter retains not only its form but also the original polish of the surface.

Crossing the smooth, bell-shaped surface, in that portion of the column in which movement has taken place, are certain faint lines which when the deformation is slight are just barely perceptible, but which become more pronounced as the deformation increases. These lines, which are uniformly spaced, or nearly so, are due to a very slight displacement along their course and are, as is well known, developed when any solid body is strained above its elastic limit. They are known as Cooper's or sometimes as Luder's lines. As seen on any one part of the lateral surface of the cylinder, they are arranged in two series which cross one another at an angle which, as nearly as it can be measured by an application goniometer, is 72 degrees. That is to say, each line makes with the vertical, which is the direction in which the pressure is applied, an angle of 36°. Along this multitude of intersecting planes, in the early stage of deformation, movement takes place with approximate uniformity, and as a result the cylinder slowly shortens, widening at the same time as described into a symmetrical, bell-shaped form which tapers down into the undeformed portion of the cylinder.

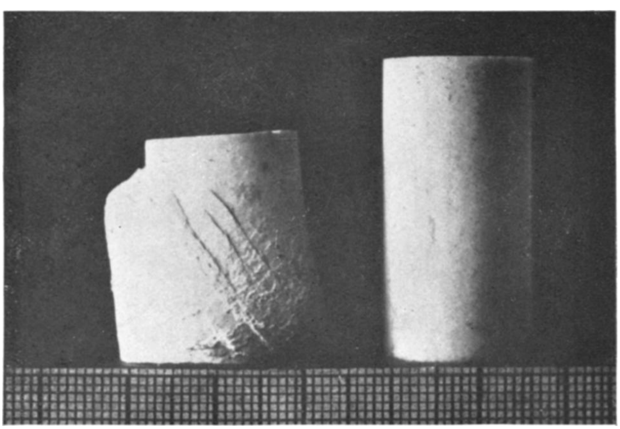
As the deformation goes forward and becomes more pronounced the movement, while still taking place simultaneously along a great number of these planes, becomes more pronounced along certain of



(*a*) Column of Carrara marble before and after deformation—using paraffin wax as an embedding material



(*b*) Column of Carrara marble before and after deformation, using alum as an embedding material



(*c*) Column of Carrara marble before and after deformation, using alum as an embedding material

them, so that, with the lateral expansion or bulging of the cylinder, there is combined a tendency for a portion of the cylinder to move more rapidly along some one plane, developing a specially pronounced shear in this direction. No rupture ensues, but the more pronounced movement in this direction is evident from the form of the distorted cylinder. This is shown in Plate IV, Fig. *a*, where the traces of such planes bound a V-shaped projection on the front of the deformed column. On the base or end face of the bulging portion of the cylinder, the lines above described are not seen, unless they be represented by a series of little, somewhat irregular radial fissures noticed where the deformation is very pronounced.

One noteworthy fact observed in every case where a cylinder of the marble was deformed in paraffine is that the column on removal of the paraffine is found to be cracked or fractured transversely, that is, in a direction at right angles to the axis of pressure. This is seen in Plate IV, Fig. *a*, where two of such fractures parallel to one another were developed in the same cylinder. The surface of such a fracture plane is approximately flat but not absolutely smooth or polished, and in partially deformed cylinders it frequently occurs just about the line between the deformed and undeformed portion. The same planes of transverse fracture are developed, upon the relief of pressure, in very strong fine-grained limestones when they are deformed in steel tubes. It is apparently connected with the elastic expansion of the rock on the removal of stress.

The invariable presence of this transverse fracture makes it impossible to determine the strength of the deformed column in compression. While probably not so strong as the original marble, it is still firmly coherent and hard, withstanding a sharp blow without breaking. When the deformation is pushed to an extreme, in addition to the Luder's lines, a series of faint, slightly wavy lines, running in a horizontal direction across the column and hence in a direction at right angles to the pressure, is developed.

When a section of the deformed marble is examined under the microscope, the decrease in transparency of the rock as compared with the original marble at once arrests the attention. This, on close examination, is seen to be due to the development of an immense number of twinning lamellae in the constituent calcite grains, often

in two or more sets crossing one another. These lamellae are very narrow, often taxing the power of the microscope to resolve them, but there is scarcely a calcite individual in the slide which is not crowded with them. It is thus evident that every individual grain in the rock has been affected by the movement and has changed its shape to a greater or less extent. When, however, the marble has been very highly deformed, movement is also seen to have taken place by granulation of the rock. In any single section the granulation has a tendency to develop along two intersecting planes, but as the deformation becomes more pronounced, the two series tend to converge and follow a more nearly horizontal course, and a single little line of granulation can often be seen to follow a minutely zigzag line running alternately in the direction of one series and then of the other, the resultant course of the line being transverse to the column and at right angles to the pressure. In this way the deformed column tends to break transversely with a slightly uneven surface, as mentioned above. It is to be noted that the marble does not show any tendency to develop a cleavage except in a direction at right angles to the pressure.

*b) Deformation with fusible metal as an embedding material.*—A column of the marble was then deformed, using fusible metal as an embedding material. The column and tube were of the same dimensions as in the experiments just described and the load required for maximum deformation was 35,000 lbs. The surface of the marble after deformation was found to be lusterless and displayed none of the intersecting lines seen when the rock is deformed in paraffine. The deformed column resembled in shape certain of the columns deformed in paraffine, but the rock itself was converted into a uniform chalky looking material which was much more friable than the marble deformed in paraffine. The mass was soaked in balsam, and thin sections were prepared from it. These, when examined under the microscope, were found to present essentially the same characters as in the case of the marble deformed in paraffine and just described. The twinning, however, was less marked and the granulation more pronounced.

*c) Deformation with sulphur as an embedding material.*—A column of marble of the same dimensions as before was then deformed

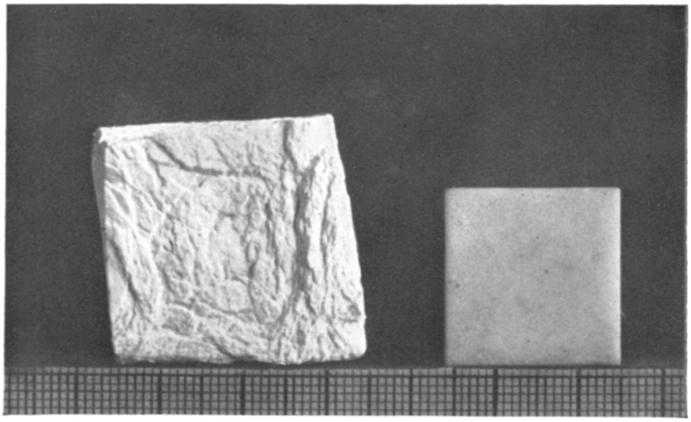
in a copper tube, also of the same dimensions as that employed in the experiments just described, but with sulphur as an embedding material. The deformation required a load of 37,500 lbs. (17,000 kilos). When the sulphur was melted away from the marble, the deformed column was found to be hard and solid, and to have been reduced in height from 1.561 inches (39.65 mm.) to 1.145 inches (29.09 mm.), a shortening of about 27 per cent. Its shape was striking, for one half of the column had sheared down over the other half, the plane of shearing making an angle of 36° with the vertical, which was the direction of pressure, and an angle of 54° with the horizontal, which is the same angle as that observed in the case of the lines traversing the surface of the marble when deformed in paraffine. This shearing movement did not take place on a single plane, but on a series of planes parallel to one another, or nearly so, and close together, giving rise to exactly the same structure as that seen in the "sheeted veins" or "shear strips" of many mining districts, as for instance at Cripple Creek. It is an excellent example of a distributed fault. The second series of lines seen in the paraffine experiments are here faintly indicated in a few places. There are no signs of rupture to be seen in the deformed column. The surface is nearly smooth, its only unevennesses being due to slight projections along the line of some of the planes constituting the distributed fault.

A series of thin sections was prepared, passing through the deformed column in a vertical direction. Under the microscope it is seen that there has been a slight movement throughout the rock, as indicated by the presence of a fine polysynthetic twinning in almost every calcite grain. This, however, has not been sufficient noticeably to flatten the grains in any direction. The chief movement is along the planes of shearing and is accompanied by a minute granulation, with the development, in many cases, of a microscopic breccia along the planes in question. The lines of shearing as seen under the microscope are not perfectly straight, but while maintaining a generally uniform course often have numerous little anastomosing branch fissures running parallel to them and occasionally crossing from one shear plane to another. The shearing thus takes place along a strip of the rock instead of in a single plane, and this strip is thus filled with a minute calcite breccia. The appearance under the

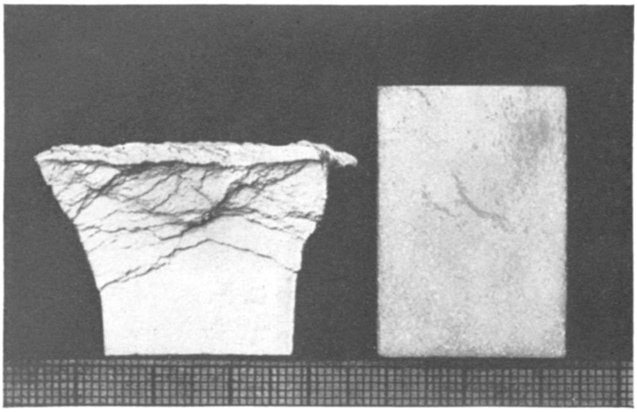
microscope is exactly that presented on a large scale by many fault planes.

*d*) *Deformation with alum as an embedding material.*—As has been shown, alum is much more resistant to deformation than either paraffine, fusible metal, or sulphur. A series of marble columns was accordingly deformed by Kick's method, employing alum as an embedding material. These were of the same dimensions as before, as were also the copper tubes employed. The maximum loads employed in the several experiments were from 35,000 lbs. to 41,500 lbs. The time of deformation was from 15 to 45 minutes. The shape presented by the deformed marble column is remarkable. The column for some distance from either end, in the earlier stages of deformation, remains intact, and these terminal portions are forced toward one another and into the middle portion of the column, which bulges outward, not however with a smooth symmetrical outline but with the development of a curious leafy form, which, when looked down upon from the end of the column, bears a resemblance to an artichoke. The leaves which wrap closely around the central stalk have well-developed, wedge-shaped points or terminations and occur in great numbers. They, however, are not arranged in regular series but each individual leaf has the appearance of overlapping others which lie beneath it. One of these curious forms is shown in Plate IV, Fig. *b*, with a column of marble of the original dimensions placed beside it.

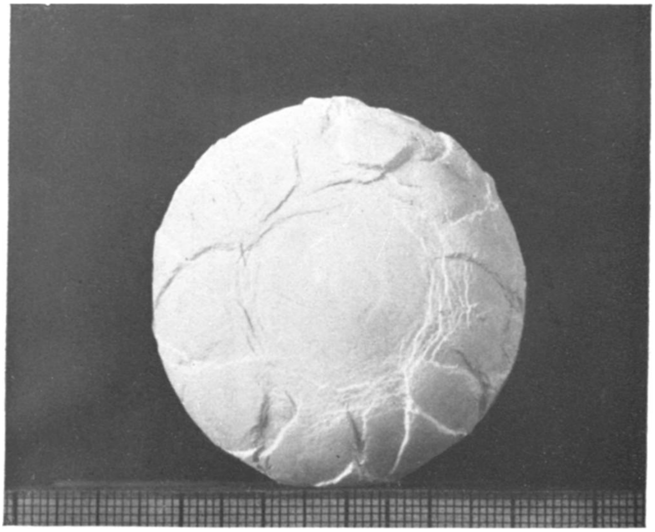
When a vertical section is cut through the axis of one of the deformed columns, the undeformed ends of the column are seen to terminate within the substance of the column in the form of rather obtuse cones pointing toward each other, and these, under the pressure, slowly advance toward one another, thin layers of the marble shearing off their faces and being forced outward, thus causing the lateral expansion of the column under deformation. As this continues, the cones at either end become gradually sheared away, and when deformation is very far advanced they eventually disappear. Each little layer of marble, however, as it is sheared off the face of the cone in the line of a tangent to it, becomes cut across by planes of movement along which other layers are being sheared off in the direction of other tangents, so that the whole medial portion of the column



(*a*) Cube of Carrara marble before and after deformation



(*b*) Prism of Carrara marble before and after deformation



(*c*) Sphere of Carrara marbel after deformation

is slowly forced outward, moving along a complicated series of intersecting planes of shearing, which gives the diamond or leaf-shaped pattern on the surface of the deformed column.

In some cases where the deformation of the tube has been less symmetrical the upper portion of the column is found to have sheared down over the lower portion, the movement being concentrated along a series of parallel planes forming a sort of distributed fault, the rock, however, still retaining its continuity and being free from fissures (Plate IV, Fig. *c*).

When a thin section of a column which has been deformed in alum is examined under the microscope, all the individual grains of calcite are found to exhibit polysynthetic twinning, showing that they have all been more or less deformed, but as before, the chief movement in the rock is seen to have taken place along planes of shearing which traverse the rock and whose course is indicated by little lines of granulated calcite. In order to ascertain the strength of the marble after deformation, two of the deformed columns were tested in compression. They crushed at loads of 750 lbs. and 850 lbs. respectively, while a column of the original rock has a crushing load of 4,380 lbs. The deformed marble, therefore, while firm, is much weaker than the original rock.

### 2. CUBES, SQUARE PRISMS, AND SPHERES

In other experiments cubes, square prisms, and spheres of the marble were deformed. In one of these a cube nearly an inch on each side was by compression in three successive copper tubes reduced to a flat cake measuring 1.36 inches by 1.38 inches and 0.55 inch thick. The maximum load employed was 219,500 lbs., or approximately 110 tons.

This deformed cube was still hard and solid and showed no traces of a pulverulent character. It is clear from its form that the movements which it has undergone are identical in general character with those which developed the artichoke structure in the case of the marble columns. On the sides of the cubes two sets of intersecting lines, along which shearing has taken place, are seen. This shearing is most pronounced at the corners of the block which tend to shear down in pieces having approximately the form of the "leaves" of the

artichoke above mentioned. On the upper surface of the flattened cake a large number of lines are seen which follow rude polygonal and more or less concentric curves around the center of the surface, which mark the borders of areas differing slightly in elevation. There are also a few vertical lines running outward toward the corners. These areas outlined on this surface are bases of rudely wedge-shaped forms which moved downward and outward. Thus the whole mass flattened out (Plate V, Fig. *a*).

A series of experiments was then made using prisms of Carrara marble. In the first of these a prism 1.575 inches high and 1.1 inches in diameter was embedded in alum in a copper tube, and the whole was squeezed down under a load of 113,000 lbs. In this experiment the tube, while retaining its original diameter at one end, spread out under the pressure at the other, and the marble column developed a graceful, rectangular, bell-shaped form, ornamented by the same beautiful pattern of triangular leaves around the end where movement had taken place. The height had been reduced to 1.2 inches (Plate V, Fig. *b*).

In the others the inclosing tube bulged at the middle in the usual manner and yielded shapes like that of the column in Plate IV, Fig. *b*, in which the zone of maximum movement was in the center of the column, which was therefore ornamented by a frill of leaflike forms in low relief. In these the load required for deformation ranged from 133,000 to 197,000 lbs., the prisms being reduced in height from 1.575 to from 1.1 to 1 inch.

A number of spheres 1.5 inches in diameter were then deformed in heavy copper tubes. By the movement the spheres were flattened to spheroids of wonderful form and beautifully ornamented, around the zone of maximum movement, by a garland of the same graceful leaflike shapes already described. The shearing which developed these spheroids is exceedingly complicated, layer after layer of the marble passing outward along the zone of maximum movement and upward toward the axes of the spheroids, each partially overlapping the one beneath, as shown in Plate V, Fig. *c*. The resulting spheroidal mass, however, is a hard, solid body of marble and shows no tendency to break in one direction rather than another. The movements, although concentrated along certain planes, do not take

place in planes of fracture, for the rock remains intact. The movement is that of a very stiff but nevertheless plastic mass.

In all the experiments just described the marble was completely surrounded by the embedding material. As the experiment proceeds, however, this flows away from about the top and bottom of the column or sphere where the pressure is greatest, and the rock is thus really caught between the upper and lower press plates of the machine, great lateral pressure however being at the same time exerted by the alum and its inclosing copper tube, and the conditions of differential pressure being thus secured.

Other experiments, however, show that a certain, though less pronounced, deformation will be produced if the marble remains in the middle of a mass of alum and is submitted only to pressure exerted by the moving alum itself, so that, if the differential pressure be of a high order, the harder limestone will be deformed by the movement of the surrounding but relatively softer matrix, provided there is not too great a difference in the relative stiffness of the two.

As a matter of interest an experiment was made to ascertain whether it would be possible to drive a nail through a mass of marble, under conditions of differential pressure such as those described above. A short nail, 0.1 inch in diameter and with a broad, flat head, was made of hardened steel. Two disks of steel were then prepared, through each of which a hole the size of the nail was drilled. A disk of marble 0.2 inch in diameter was then placed between the two steel disks and the nail was placed in the hole in the upper steel disk, so that it rested in a vertical position on the center of the marble plate. The whole was then placed in a copper tube and embedded in alum in the usual manner. Pressure was then applied and the whole was squeezed down. On dissolving away the alum the upper steel plate was found to have been distinctly bent by the moving alum, the head of the nail was broken into small pieces, but the shank of the nail had passed completely through the marble disk, making a clean, well-defined hole in the upper portion and shoving out a little conical-shaped piece of marble before it on the lower surface of the disk. The marble showed no trace of crack or fissure—the steel had passed directly through its substance. A photograph of the plate upon the completion of the experiment is shown in Plate VI, Fig. *a*, a new

nail of the same dimensions as the former one being inserted in the hole made by the latter.

### B. LITHOGRAPHIC LIMESTONE: SOLENHOFEN, BAVARIA

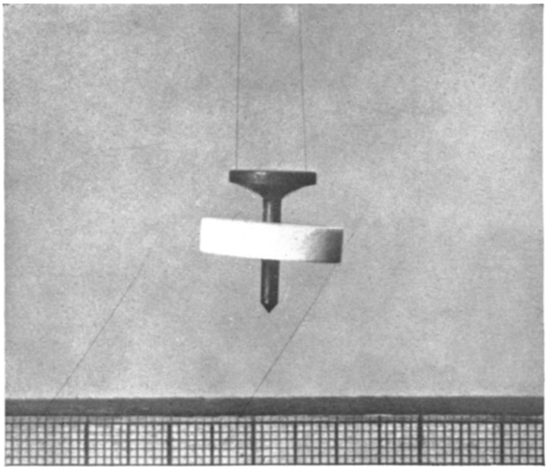
This is a buff-colored limestone of extremely fine and absolutely uniform grain, containing about $3\frac{1}{2}$ per cent of various impurities. It breaks into a splintery or conchoidal fracture. When a column of this rock is deformed in paraffine the result is similar to that obtained with Carrara marble, and in almost every case the same transverse cracks develop upon the removal of the embedding material.

In an experiment in which the rock was deformed in alum the column presented one of those highly interesting forms sometimes seen in deformed Carrara marble, dolomite, etc. This is produced by the development of a complete system of minute parallel faults crossing the column at an angle of 65° to the horizontal. The upper portion of the column thus tends to shear down along these planes, the rock however remaining hard and solid, indicating a deformation under conditions intermediate between those of the zone of fracture and the zone of flow, but more nearly approximating those of the latter.

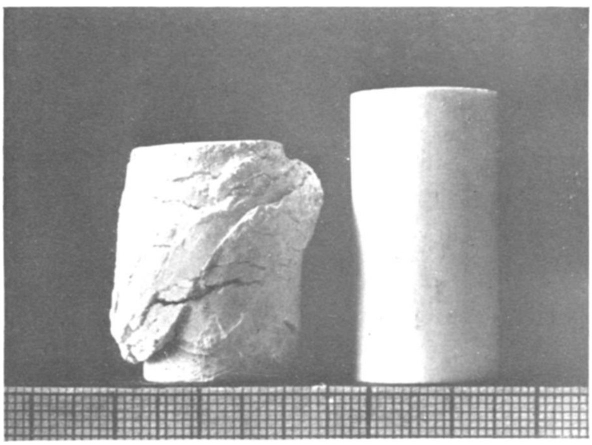
### C. FOSSILIFEROUS LIMESTONE: BELGIUM

This is a dark-gray, highly fossiliferous limestone.

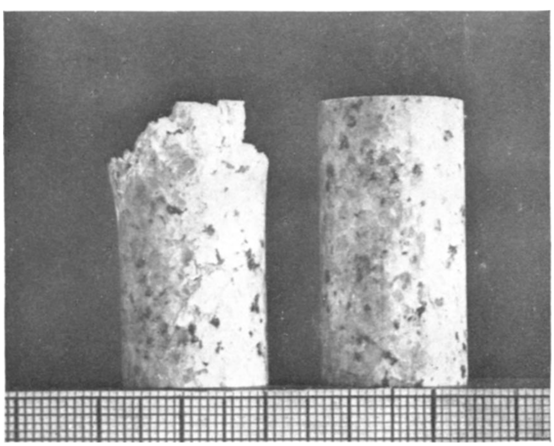
A column was embedded in alum and deformed in the usual manner. The height of the column was reduced from 1.574 inches to 1.4 inches, and the column yielded to pressure in such a manner that instead of bulging symmetrically it developed a movement exactly like that described in the experiment with Solenhofen limestone; that is to say, the upper portion of the column moved down over the lower portion at an angle of about 45°, the movement being concentrated along a strip about half an inch wide. In this strip there were several parallel planes in which the movement was especially pronounced, but within this zone the whole mass was seen to have been more or less plastic. Thin sections of the rock in this portion of the column when examined under the microscope showed little lines of minutely granulated material, often presenting a minutely brecciated structure, the whole constituting a species of "distributed fault." The rock after deformation was apparently as hard and solid as before.



(*a*) Steel tack forced through marble disk by differential pressure



(*b*) Dolomite—Cockeysville, Md.—before and after deformation



(*c*) Column of Baveno granite before and after compression

### D. BLACK MARBLE: BELGIUM

This is the well-known ornamental stone which in commerce is known as "Belgian Black" or "Noir Fin." It is an impure, somewhat bituminous limestone, which is impalpably fine in grain, breaking with a splintery fracture like glass, and which takes a very high polish and is extensively used for interior decoration.

When thin sections are examined under the microscope the rock is found to be so fine in grain that a high power is necessary to resolve it. It is composed of minute calcite grains from 0.02 mm. to 0.002 mm. in diameter and of irregular shape, between and around which are occasional minute films and spots of a black color.

When submitted to compression in paraffine it gave rise to forms identical with those developed in the Solenhofen limestone under the same conditions.

When sulphur was employed as an embedding material, the ends of the column were found to have been forced into the central portion, with the consequent development on the exterior surface of a most complicated series of little tongues or wedge-shaped portions of the rock, sheared up one upon the other like overlapping shingles, thus giving rise to a corresponding increase in the thickness of the deformed column as its height is reduced. The rock after deformation remained hard and solid; it could be rapped sharply on a table without breaking. The cohesion may have been due in part to a little sulphur which had soaked into the column, acting as a cementing material. No trace of sulphur, however, could be detected on the surface of the column, the heat to which it was subjected after the sulphur had melted and drained away having entirely volatilized any portion of that substance that still remained adhering to the rock.

When alum was employed, the surface of the deformed column was found to be covered with a great number of sharp and more or less wedge-shaped pieces, often separated by minute open cracks, of which a great number traverse the column. The end faces of the column were also divided into separate areas, often separated by open cracks, which areas form the bases of wedges which have been faulted up or down. The resulting form is similar to that obtained when the rock is deformed in sulphur. The little wedges showed no evidence of plastic deformation. The rock was broken in a marvel-

ously complicated manner, but there no plastic flow was discernible. The rock under the conditions of the experiment acts essentially as a brittle body.

E. DOLOMITE: COCKEYSVILLE, MARYLAND

This is a typical dolomite, the analysis showing that the carbonates of lime and magnesia are present very nearly in their molecular proportions. It is white in color, practically free from impurities, perfectly crystalline, of medium grain, and is extensively employed as a building stone.

A column when deformed in paraffine wax in the usual manner was found upon the completion of the experiment to have assumed the same form as in the case of Carrara marble. The upper portion, where the deformation was greatest, showed very plainly two sets of lines crossing its surface and intersecting at angles of about 60°. The upper end of the column at a number of places was commencing to shear down in triangular-shaped masses. From the portion of the column where the deformation had been greatest a series of thin sections was prepared. When these were examined under the microscope the rock was seen to be traversed by many little branching lines of finely granulated material, which lines however intersected, giving a rude, diamond-shaped network. The individuals composing those portions of the rock between these lines were somewhat flattened in shape and showed distinct strain shadows.

The dolomite was then deformed in alum in the usual way, the load required being 33,000 lbs. The deformed column presented a striking appearance and showed in a most beautiful manner on its surface the leaflike forms due to movements along Luder's lines, described in the case of the Carrara marble, but the dolomite is seen to be somewhat less plastic than the Carrara marble, for in several places the column was torn by the movement in directions other than those followed by Luder's lines, this tearing giving rise to open and ragged rents in the substance of the column after the alum had been dissolved away. The form is very suggestive (Plate VI, Fig. *b*). The rock moved as an exceedingly stiff, semi-plastic mass. The upper portion of the column is commencing to shear off along a plane inclined at an angle of about 60° to the horizontal. The movement

however is, as has been mentioned, that of a stiff paste, not that of a brittle solid.

### F. IMPURE MAGNESIAN LIMESTONE: HULL, CANADA

This is a very impure magnesian limestone, containing about 50 per cent of insoluble residue in the shape of minute subangular grains of clear quartz. The rock is of somewhat open grain and porous character and has been used very extensively for the production of hydraulic cement.

When deformed in paraffine, triangular portions of the column were found to have sheared off around the end, as in the case of other purer varieties already described. These remain adhered to the column, which also shows a marked tendency to develop cracks, crossing it at right angles to its length, i.e., at right angles to the direction of the pressure.

A column of the usual dimensions was then deformed in alum in the usual manner under a load of 31,000 lbs. On dissolving away the alum, however, the deformed column went to pieces, but from the shape of the fragments it could be seen that the movements developed in it had been of the nature of a complicated shearing similar to those already described.

### G. BIOTITE GRANITE: BAVENO, ITALY

Columns of granite of the usual size and with a polished surface were embedded in alum inclosed in a copper tube in the usual manner and submitted to the pressure required to squeeze the whole down until the copper tube displayed signs of incipient rupture. The load required for this purpose was 50,000 lbs.

When the alum was removed by solution, the granite at one end of the column was found to have remained intact. Toward the middle, however, the column had undergone a distinct bulging due in part at least to a movement along little planes of thrust or shearing, although the work was still quite coherent, the movement in question having given rise to a rude gneissic or schistose structure owing to the arrangement of strings of mica and grains of orthoclase parallel to the base of the column. The other end of the column where the motion had been greatest was disintegrated by the movement and fell

to powder when the alum was dissolved away. A photograph of one of the columns as it appeared when freed from the alum is shown in Plate VI, Fig. *c*, but as in this particular case the movement was not so great as in others, the gneissic structure referred to is not well seen. When examined under the microscope, both quartz and orthoclase show well-marked strain shadows, but even a very careful examination under a high power between crossed Nicols fails to show with certainty whether the shadows in question are due to an actual bending of the mineral or to a fracture of the mineral with a slight shifting along an infinite number of ultra-miscroscopic cracks.

In several cases, however, where the conditions for observation were very favorable, no signs of such cracks could be detected and the mineral seemed to have undergone an actual twisting.

The biotite individuals had been very distinctly bent and twisted.

The rock displays a remarkably perfect cataclastic structure along certain lines or streaks where the quartz and orthoclase are represented by larger fragments, which, however, are mingled with those of smaller size, as well as with others which pass into almost ultra-microscopic dimensions.

## SUMMARY

1. Under the differential pressures developed by this method of experimentation, that is by employing Kick's process, using fused alum or the other embedding materials employed, and tubes of copper with walls of from 0.125 to 0.25 inch (3.175 to 6.38 mm.) in thickness, minerals which have a hardness of 5 or under (Mohs's scale), show distinct plastic deformation, this deformation being less pronounced in the case of the harder minerals.

2. The minerals above 5 on the Scale of Hardness, while not presenting any marked change in shape, in some cases show evidences of internal movement. Thus a perfect basal twinning is developed in diopside, similar to that so often seen in specimens of this mineral from the crystalline limestones of the Grenville series.

3. In the case of very hard minerals, no evidence of plastic flow was discernible; their structure was broken down and they were reduced to powder.

4. Under the differential pressure fluorspar not only changed its form but also its color.

5. The softer rocks, such as Carrara marble, are readily deformed, the shapes assumed varying somewhat with the character of the material in which the rock is embedded during deformation. The movement takes place in part by distortion of the calcite grains and in part by the development of a cataclastic structure in the rock.

6. Crystalline dolomite is more resistant. The movement induced in it resembles that produced in a very stiff paste. This movement takes place chiefly through the development of cataclastic structure.

7. Very fine-grained massive limestones display a movement in which flowing and fracture are combined.

8. The harder rocks, like granite, crumble under the pressure, although in those places where the movement is very slight, the rocks develop an indistinct foliated structure owing to the granulation (cataclastic structure), with movements in the granulated portion of the rock.

9. For the development of a flow structure in the harder rocks, much higher differential pressures are required than are obtained by this process—such differential pressures, for instance, as may be secured when the rocks are inclosed in steel before being submitted to the deforming load.